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Mitigating Particulate Matter Generations in a Commercial Cage-free Henhouse

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Abstract

Compared to conventional cage production systems, cage-free (CF) hen housing offers hens more space and opportunities to exercise their natural behaviors (e.g., perching, dust bathing, and foraging). However, CF housing poses a number of inherent environmental challenges, among which are high levels of particulate matter (PM) and ammonia (NH3). Spraying water on CF henhouse litter (e.g., 125 mL m-2 per cm litter depth) has been shown to mitigate generation of PM by 60-70% in our previous lab-scale tests. The objectives of this study were to verify the lab-study findings of PM reduction in a commercial CF henhouse in central Iowa and to evaluate the indoor air quality (e.g., PM and NH3 concentrations) and litter moisture content affected by water spray. The commercial CF house had a nominal capacity of 50,000 laying hens, measuring L×W×H = 154 × 21.3 × 3.0 m). A water sprinkling system was installed in half of the henhouse in the length direction (treatment section), whereas the other half of the henhouse served as the control. For each of the three trials conducted during winter of 2017-2018, spray dosage (125 mL H2O m-2 per cm litter depth) was set according to the initial litter depth before spray. Results show that PM concentration was reduced by 37-51% PM in the treatment section of the CF henhouse. The lower reduction efficiency in the field than in the lab tests was partially attributed to the fact that water spray in the commercial henhouse was applied to only the open litter area, and not the litter area under the aviary system due to limited space. Adjusting spray dosage according to litter depth is necessary for maintaining the appreciable reduction efficiency. Litter moisture content of the treatment section was 9-14% higher than that of the control (15.6% vs. 14% in Trial 1, 14.6% vs. 12.2% in Trial 2, and 17.7% vs. 14.9% in Trial 3), but NH3 concentrations in the treatment and control sections were similar during the test.

Keywords

Alternative hen housing, air quality, litter moisture content, dust

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MITIGATING PARTICULATE MATTER GENERATIONS IN A COMMERCIAL CAGE-FREE HENHOUSE

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ABSTRACT.

Compared to conventional cage production systems, cage-free (CF) hen housing offers hens more space and opportunities to exercise their natural behaviors (e.g., perching, dust bathing, and foraging). However, CF housing poses a number of inherent environmental challenges, among which are high levels of particulate matter (PM) and ammonia (NH_3). Spraying water on CF henhouse litter (e.g., 125 mL m^{-2} per cm litter depth) has been shown to mitigate generation of PM by 60-70% in our previous lab-scale tests. The objectives of this study were to verify the lab-study findings of PM reduction in a commercial CF henhouse in central Iowa and to evaluate the indoor air quality (e.g., PM and NH_3 concentrations) and litter moisture content affected by water spray. The commercial CF house had a nominal capacity of 50,000 laying hens, measuring L×W×H = 154 × 21.3 × 3.0 m). A water sprinkling system was installed in half of the henhouse in the length direction (treatment section), whereas the other half of the henhouse served as the control. For each of the three trials conducted during winter of 2017-2018, spray dosage (125 mL H_2O m^{-2} per cm litter depth) was set according to the initial litter depth before spray. Results show that PM concentration was reduced by 37-51% PM in the treatment section of the CF henhouse. The lower reduction efficiency in the field than in the lab tests was partially attributed to the fact that water spray in the commercial henhouse was applied to only the open litter area, and not the litter area under the aviary system due to limited space. Adjusting spray dosage according to litter depth is necessary for maintaining the appreciable reduction efficiency. Litter moisture content of the treatment section was 9-14% higher than that of the control (15.6% vs. 14% in Trial 1, 14.6% vs. 12.2% in Trial 2, and 17.7% vs. 14.9% in Trial

3), but NH_3 concentrations in the treatment and control sections were similar during the test.

Keywords. *Alternative hen housing; air quality; litter moisture content; dust.*

INTRODUCTION

Concerns over animal welfare among general public and marketing decisions have led to pledges by a number of U.S. food retailers and restaurants to source only cage-free (CF) eggs by 2025 (Xin, 2016). Based on the current number of pledges, it would take more than 70% of the current US layer inventory to meet the pledged demand by 2025 (Xin, 2016; UEP, 2017). Compared to conventional cage production systems, CF hen housing offers hens more space and opportunities to exercise their natural behaviors (e.g., perching, dust bathing, and foraging). However, CF housing poses environmental challenges, such as high levels of particulate matter (PM) and ammonia (NH_3), especially during cold weather when the house has limited ventilation (Takai et al., 1998; Hayes et al., 2013; Zhao et al, 2013, 2015; Shepherd et al., 2015).

Rodenburg et al. (2005) concluded that poor air quality in CF systems would affect health and hygienic status of birds. David et al. (2015) reported that high dust levels in CF systems might compromise the health and welfare of both birds and their caretakers. Zhao et al. (2015a) reported that PM_{10} (particulate matter with aerodynamic equivalent diameters ≤10 micrometers) levels in CF houses (~4 mg m^{-3}) were 6-9 times higher than conventional cage manure-belt and enriched colony houses. Moreover, PM_{10} levels in CF henhouses are much higher than the 24-h concentration threshold of 150 μg m^{-3} set by the U.S. Environmental Protection Agency to protect public welfare (U.S. EPA, 2015). Higher levels of PM in CF houses can carry more airborne microorganisms and endotoxins which, once inhaled, may cause infection or trigger respiratory diseases to animals and/or their caretakers (Cambra-López et al., 2010; Zhao et al, 2016). Air quality is one of the important health or welfare indicators for animals (Mostafa and Buescher, 2011; Mostafa et al., 2016 a, b; Mostafa et al., 2017). Furthermore, high PM emissions from CF houses have become a major environmental challenge that may trigger the requirement of U.S. Clean Air Act Title V permits (U.S. EPA, 2018). Therefore, suppressing PM levels is imperative to protecting the health and well-being of the animals and the caretakers, and hen improving the environmental stewardship of CF egg farming (Xin et al., 2011; U.S. EPA, 2015; Ru et al., 2017).

The high PM levels in CF henhouses primarily stem from the hen activities on litter floor. Spraying liquid agents onto litter floor, such as tap water, acidic water, electrolyzed water, and mixture of water and soybean or canola oil, has been shown to reduce dust level or airborne microbial concentrations of poultry houses (Ellen et al., 2000; Zheng et al., 2014; Adell et al., 2015; Winkel et al., 2016). Zheng et al. (2014) sprayed regular tap water and slightly acidic electrolyzed water (AEW) at 80 mL m^{-2} onto laying-hen litter, which reduced PM by 49%. There was no difference between tap water and AEW in PM reduction. In a lab-scale study that simulated CF environmental setting (mechanically stirred CF litter), Chai et al. (2017) reported that spraying AEW at dosages of 25, 50, and 75 mL [kg dry litter]$^{-1}$d^{-1} reduced PM levels by 71%, 81%, and 89%, respectively, immediately after spraying. The PM reductions were still significant after 24h of spraying, averaging 57% to 83%. However, high dosage of spray enhanced NH_3 emissions as litter moisture content increased in proportion to the spray dosage (Chai et al., 2017). Ogink et al. (2012) reported that spraying 150-600 mL m^{-2} water on the litter manually twice a day reduced PM level by 18-64% in a room scale house (around 600 hens), although it increased NH_3 emissions by 21% to 65% in CF henhouses in the Netherlands. Housing styles (e.g., scale or size), management practices (e.g., litter access), climatic conditions (hence ventilation), and litter quality of CF housing systems in the US can considerably differ from those in Europe, which warrants evaluation of PM mitigation strategies under US production conditions. Ammonia elevation is one of the primary concerns of water spray methods. Because pH of a spray agent affects ammonium-ammonia (NH_4^+-NH_3) equilibrium in the litter/manure (Groot Koerkamp, 1998; Ni, 1999), application of low pH liquids (e.g., water with a pH of 3) to litter would help control PM and ammonia at the same time. However, concerns exist about the potential corrosive effect of acidic liquid on housing equipment (Chai et al., 2017). Chai et al. (2018a) conducted a lab-scale study that involved spraying neutral electrolyzed water (pH=7-8) at 125 mL m^{-2} (at 1 cm litter depth) and applying poultry litter additive/treatment (PLT, sodium bisulfate, $NaHSO_4$) at 30 g per kg dry litter onto CF henhouse litter. The authors reported reduction of 60-70% in PM generation and 70-80% in NH_3 generation. Chai et al. (2018a) also showed that properly controlling water spray dosage could provide >60% PM reduction efficiency without causing an increase in NH_3 concentrations.

The objectives of this study were (1) to verify the lab-scale study findings of PM reduction based on the identified spray dosage (e.g., 125 mL m^{-2} per cm litter depth) of neutral water or farm tap water in a commercial CF henhouse; and (2) to evaluate indoor air quality (PM and NH_3 concentrations) and litter moisture content as affected by the water spray in a commercial CF henhouse.

MATERIALS AND METHODS

LAYING-HEN HOUSE AND SPRINKLING SYSTEM

This PM mitigation verification study was conducted in a commercial CF henhouse (154 L × 21.3 W × 3 H m) with a nominal capacity of 50,000 hens (DeKalb White) located in central Iowa (fig. 1). Resource allocations per hen in the CF house averaged 520 cm^2 forage area (litter floor), 547 cm^2 wire mesh flooring area in the aviary system (Big Dutchman, an open and multi-tier system with perches, feed, and water at different levels), 86 cm^2 nest space, 11.7 cm perch space, and 10.2 cm feeder space. The total available space was 1250 cm^2 hen^{-1}. Manure belts were run one-third length per day, making it a 3-day removal interval for manure on the belts. More details of cage-free or aviary system description can be found in Zhao et al. (2015b) and Figure 2. Litter on the floor was cleaned approximately every 3 months. After cleaning, 30 bags (9.1 kg per bag) of pine shavings were applied on to the 2800 m^2 concrete floor (~0.1 kg m^{-2}). The house had solid sidewalls. Cross-ventilation was used and operation of the fans (sixteen 1.32 m dia. fans and four 0.91 m dia. fans in total) was controlled based on indoor air temperature. All the exhaust fans were installed on the sidewall by Row 1. Fresh air came from the ceiling box inlets (two-way, 144 in total) above the two inspection aisles and aviary system (fig. 1). Supplemental heat with combustion of liquid propane (four forced air heaters with a total heating capacity of 293 kW or 1,000, 000 BTU) was provided, as needed. The heated air was distributed through the air duct above manure belts, which facilitated uniform heat distribution while drying the manure at the same time. The CF house lights were on from 4:45 to 20:00. The birds were allowed access to the litter floor from 10:00 to 20:00 during Trial 1, and the water was programmed to spray at 9:50. After November 15, 2017, the farm stopped closing the system doors at night, and consequently the birds accessed the litter floor beginning 4:45 when the lights were turned on.

Half of the house (77 m × 21.3 m) was equipped with a sprinkling system (Weeden Environments Inc., Ontario, Canada), whereas the other half of the house (without sprinkling system, fig. 3) served as the control. Water was sprayed automatically by programming the controller for start time, spray period, and interval time. The CF house had four rows of litter floor, denoted as R1 through R4 in figure 1 (see dimensions in figure). Each row was divided into 10 sections (S1-S10) by metal wire mesh with pass-through doors, hence a total of 40 zones of litter floor (fig. 1). S1-S5 were the treatment sections (highlighted in yellow) and S6-S10 were the control sections. No sprinklers were installed for the litter area beneath the aviary structure system due to limited space (0.40-0.45 m high), where the birds' activities and dust generation were observed to be much lower than in the open litter floor areas. Besides, the hens could peck at and damage sprinklers within their reach, as would be the case under the structure system.

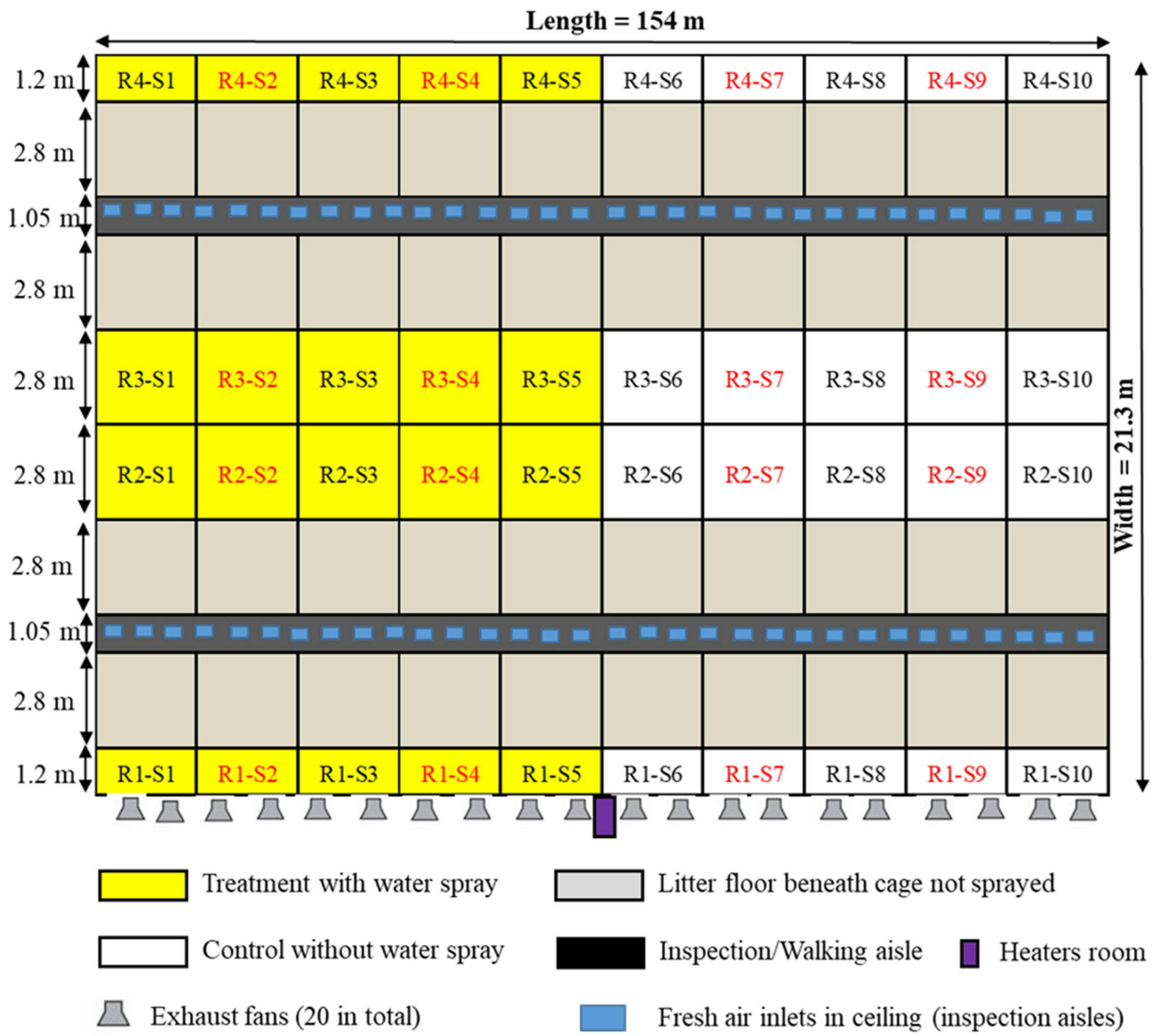


Figure 1. Schematic diagram of cage-free house and experiment arrangement: test (treatment) and control litter floor zones (R-row, S-section; zones with red labels were monitored for environmental conditions and for litter sampling).

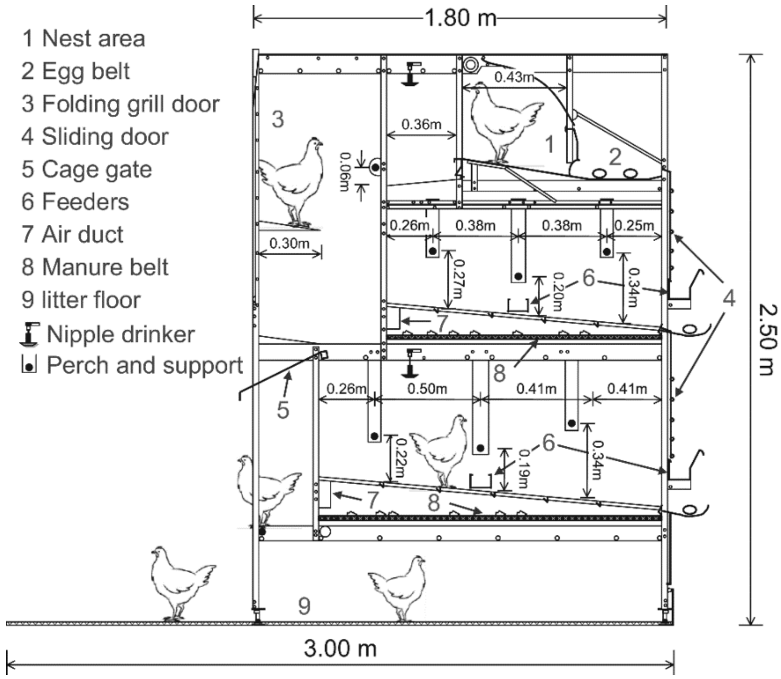


Figure 2. Schematic illustration of aviary cage-free system (Zhao et al., 2015b).

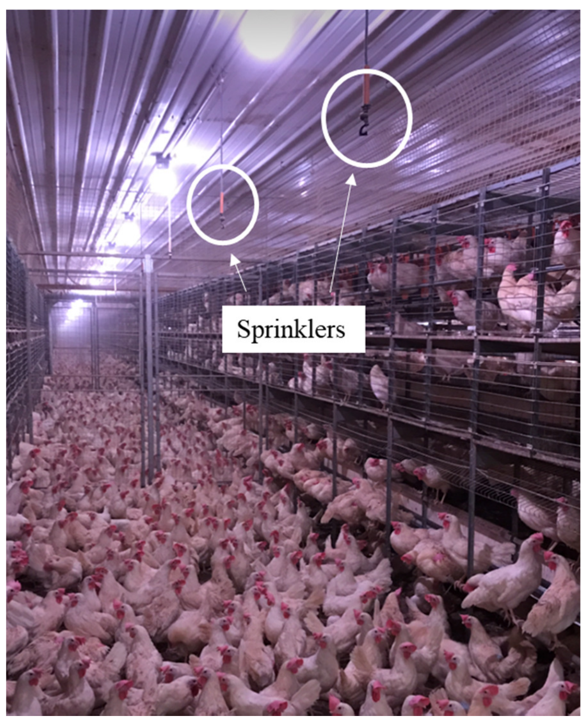


Figure 3. Experimental setup: sprinklers installed in the cage-free henhouse.

Due to difference in the widths of the rows, two types of sprinklers were installed 2.2 m above the litter floor. Twelve bow-tie sprinklers (nozzle model is DAN-blue-180°, rated water output is 43 L h^{-1} at 276 kPa, each covering an area of 1.0 m W ×

6.2 m L = 6.2 m^2, DAN Sprinklers, Netherlands) was installed in each of R1 and R4 (the narrow litter rows). In each of the two middle (wider) rows (R2 and R3), 29 spiral sprinklers were installed (nozzle model is DAN-orange-360°, rated water output is 35 L h^{-1} at 276 kPa, each covering a 2.8 m dia. circle or 6.15 m^2 area, DAN Sprinklers, Netherlands). In total 82 sprinklers were installed in the treatment section. Flow rate of the sprinklers (at the beginning, the middle, and the last part of the sprinkle line) in each row was checked with measuring cylinder before each trial. The values in the able 1 reflect the spray time based on the flow measurement check. The spiral sprinklers agreed well with the rated flow rate over the three trials, only slightly lower in Trial 3 (33.5 L h^{-1} vs. 35 L h^{-1} for middle rows), but the bow-tie sprinklers showed over 20% higher flow rate than the rated values for all trials. The tap water line pressure in the CF house was 55-60 psi (379-414 kPa) which was reduced to 40 psi (276 kPa) by the sprinkling system controller for all the sprinkler lines.

Commercial litter additive (sodium bisulfate, $NaHSO_4$) that had been tested effective for NH_3 control was prepared in case the liquid spray caused elevation of NH_3 levels (Chai et al., 2018a); but it was never used because the treatment section did not show appreciably higher NH_3 than the control during the test. The farm water line (water pH=7.7) was used to spray water for the dust control.

The water spray dosage of 125 mL m^{-2} based on 1 cm litter depth had been shown to achieve over 60% PM reduction without causing NH_3 elevation in the lab study (Chai et al., 2018a). This spray dosage was used as the base and adjusted proportionally according to the litter depth. The PM mitigation test was conducted during winter of 2017-2018 (October 26, 2017 to January 25, 2018) when the CF house had high PM levels due to reduced building ventilation rate (Zhao et al., 2015). The spray was done once per day, 10 min before the hens' access to the litter floor (table 1). In each of the three sequential trials, the once-a-day water spray continued for 14 d, then stopped for at least 14 d before starting another round of spray (table 1). Because PM level and litter moisture content (LMC) had been shown to return to the control levels by day 18 (i.e., 4 days after stopping the spray), measurement of PM concentrations stopped after day 18 for instrument maintenance. However, measurements of LMC and other environmental conditions of NH_3, CO_2, temperature and RH continued till day 28.

Table 1. Spray dosage for different litter depths [1]

	Trial 1	Trial 2	Trial 3
Frist spray	10/26/2017	11/24/2017	12/29/2017
Last spray	11/8/2017	12/7/2017	1/11/2018
Initial litter depth, cm	0.5	1.0	1.4
Spray dosage, mL m^{-2}	62.5	125	175
Spray time (spiral sprinkler-wider row), s	40	80	115

Spray time (bow-tie sprinkler-narrow row), s	22	44	64

Note: [1] In each trial, once-a-day water spray continued for 14 d, and then stopped for at least 14 d to let litter dry before starting the next trial.

ENVIRONMENTAL FACTORS MONITORING

During each trial, air temperature (T), RH, CO_2, NH_3 and PM were monitored (at 1 m height above floor except for PM and NH_3) either continuously or periodically in 8 locations (in the geographical center of the zones labeled in red in fig. 1) on d0 (one day before the first water spray), d1, d4, d7, d10, d13, d15, and d18; whereas CO_2 concentration was measured at two locations (R3-S3 and R3-S8) with HOBO MAX Logger (ONSET, Bourne, MA, USA). Time interval for the continuous measurements of T, RH, and CO_2 measurements was 10 min. Ammonia concentrations at each of the 16 locations were monitored (at 0.35 m height the same as PM measurement) with a single portable electrochemical NH_3 sensor (0-100 ppm measurement range, GasAlert, BW Technologies Ltd., Arlington, TX, USA), 2 min per location, in the following sequence: R1-S2, R1-S4, R1-S7, R1-S9, R2-S9, R2-S7, R2-S4, R2-S2, R3-S2, R3-S4, R3-S7, R3-S9, R4-S9, R4-S7, R4-S4, and R4-S2. The NH_3 sensor was checked biweekly with standard calibration gases (zero gas of N_2 and span gas of 26.3 ppm NH_3 with N_2 balance). Linear regression equations were developed to correct the sensor readings, if needed, based on the calibration. Average NH_3 levels for the treatment (n=8) and control (n=8) sides were compared to assess the water spray (treatment) effect.

An optical PM monitor (Dusttrak Drx Aerosol Monitor 8533, TSI Incorporated, Shoreview, MN, USA) was used to measure PM concentrations of different particle sizes, i.e., PM_1, $PM_{2.5}$, PM_4, PM_{10} and total suspended particulate (TSP), at the same locations and sequence as the NH_3 measurements, 2 min per location. The first 30 s reading was not used considering the potential interference of sensor relocation. Besides, the PM monitoring was primarily at 0.35 m above the litter floor (fig. 4) near the center of each selected monitoring section. As with NH_3, average PM levels of treatment (n=8) and control (n=8) sides were compared to assess the water spray (treatment) effect. In addition, PM levels at the heights of 0.25 m, 0.5 m, 1 m, 1.5 m, and 2 m above litter floor at four locations (i.e., R2-S2, R2-S4, R2-S7, and R2-S9) (fig. 1) were monitored to assess vertical stratifications on October 24, 2017 (starting at 10:00), two days before the first water spray of Trial 1. The TSI PM monitor was zero calibrated weekly and sent back to the manufacturer for a multi-point calibration twice during the test (once immediately before the test and then in the middle of the test). Outdoor air temperature and RH were monitored with HOBO MX2300 (ONSET, Bourne, MA, USA).

Figure 4. PM monitoring in the cage-free henhouse at 0.35 m above floor (inlet of Dusttrak was at the birds' level).

Litter sampling and moisture content (LMC) measurement

Litter was sampled periodically (d0, d1, d4, d7, d10, d13, d15, and d18 in each trial) and stored in new zip-loc bags at the same 8 locations (fig. 1) where PM and NH_3 were monitored in both the control and the test treatment. LMC of the collected samples was determined by oven-drying approximately 10 g samples at 105 °C for 24 h, and was expressed on a wet basis.

Data analysis

The results of d0 were used to check if there was existing difference in PM, NH_3, or LMC between the treatment and control sections before water spray. In each trial, the means of d1, d4, d7, d10, and d13 for treatment (monitored at 8 locations) and control (monitored at 8 locations) were used to determine PM reduction efficiency. Average PM level of measurement periods on d15 and d18 was used to assess rebounding from the treatment effect.

Statistical analysis of the PM reduction efficiency was performed using R software version 3.3.3 (R Core Team, 2014). Tukey's honest significant difference (HSD) and linear model (lm) were applied to test the effect of water spray on PM and NH_3 emissions. Equation 1 lists the statistical model for the data analysis (Faraway, 2016). Differences in PM or NH_3 levels between the treatment and control were considered significant at $p<0.05$.

$$Y_i = \mu + L_i + e_i \qquad \text{Eq.1}$$

Where Y_i denotes the independent observation (e.g., PM, NH_3 or LMC) for water spray dosage i;

μ is the overall mean;

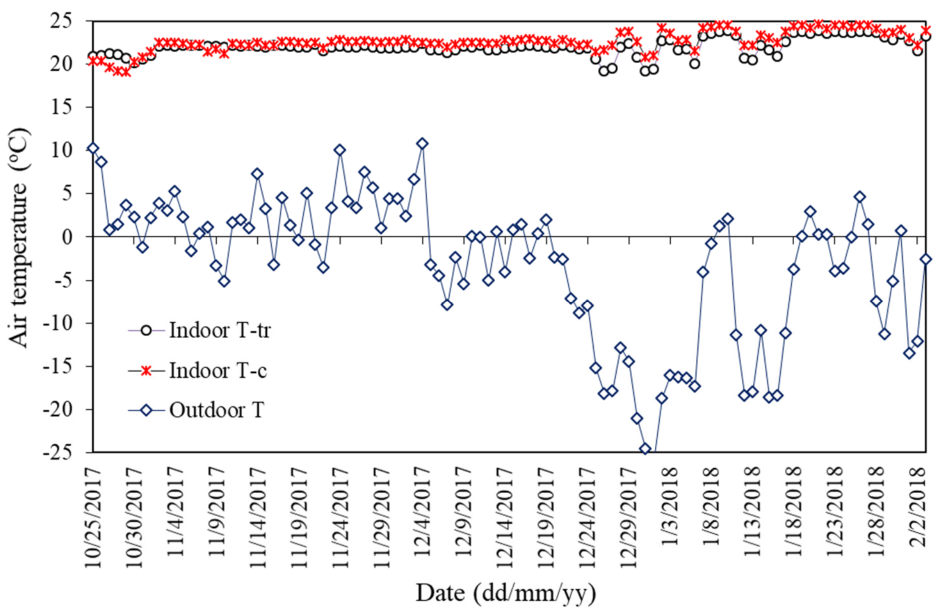
L_i is the water spray effect (fixed);

e_i is the random error with $N\sim(0, \sigma^2)$ (normally and independently distributed with mean 0 and variance σ^2).

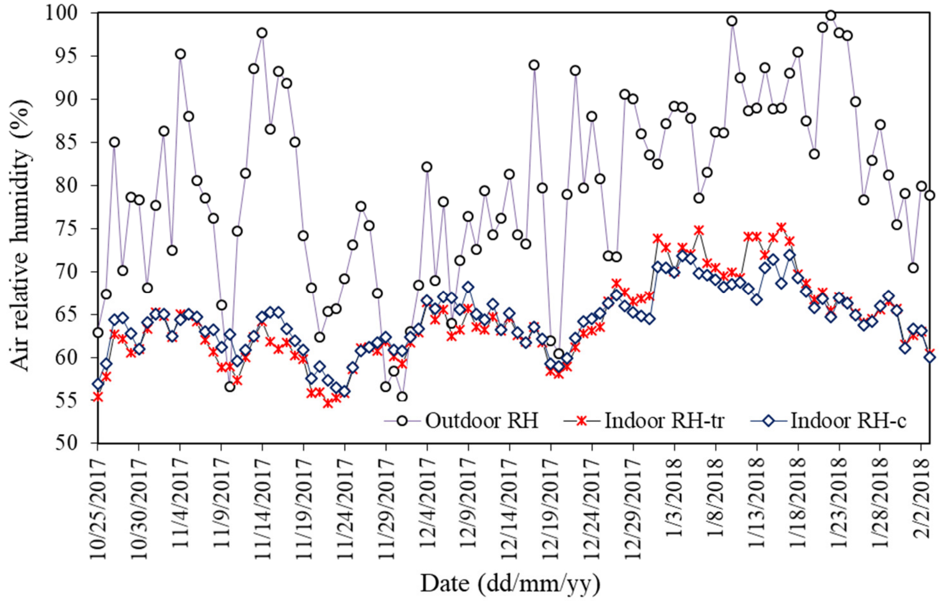
RESULTS AND DISCUSSION

HENHOUSE THERMAL ENVIRONEMNT AND CO_2 CONCENTRATION

Air temperature (T) and RH of the control and treatment sections along with the outdoor values are shown in Figure 5. Indoor T was relatively constant (20 °C - 24 °C with RH of 55% - 70%) during the test because supplemental heating was applied as needed. The control and treatment sections had similar indoor T (fig. 4-a), RH (fig. 4-b) and CO_2 concentrations (fig. 6) during the test (winter of 2017-2018). The low pressure sprinkling applied for a short duration might have only a slight cooling effect. CO_2 concentrations spiked in late December 2017 when outside T was low and VR was reduced to the minimum.



(a) Indoor and outdoor air temperature



(b) Indoor and outdoor air relative humidity

Figure 5. Daily mean air temperature (T) (a) and RH (b) in the treatment (T-tr, RH-tr) and control (T-c, RH-c) sections of the cage-free henhouse and the outdoor T and RH. Each mean value is an average of 10-min observations.

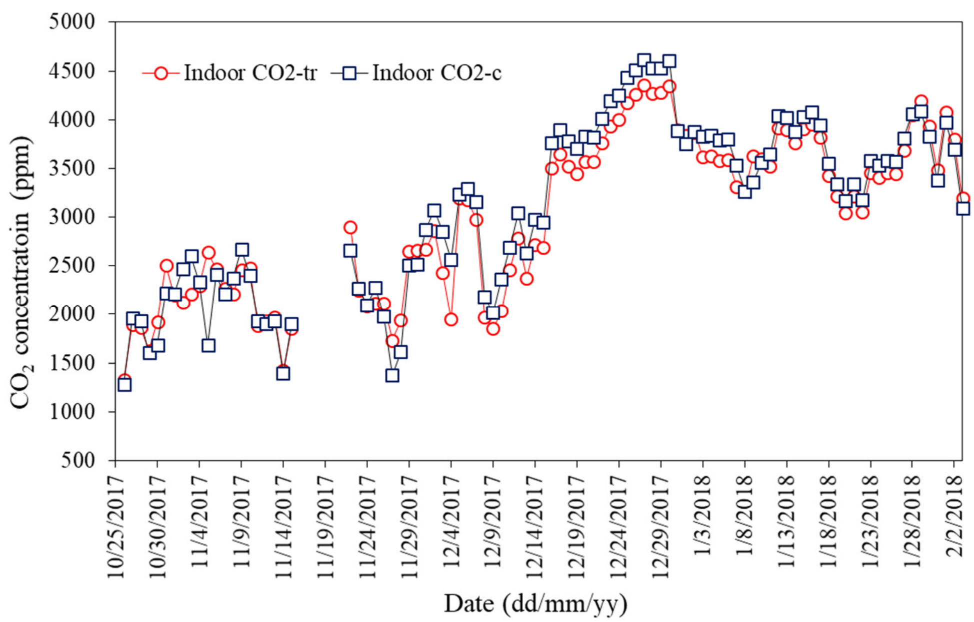


Figure 6. Daily indoor CO_2 concentrations in the treatment (CO_2-tr) and control (CO_2-c) sections of the cage-free henhouse. Each mean value is an average of 10-min observations.

LITTER MOISTURE CONTENT (LMC) AND NH_3 CONCENTRATION

The treatment and control had similar LMC before water spray. After spraying water once-a-day, LMC in the treatment increased gradually (table 2). LMC in the treatment was higher than control in each of three trials (fig. 7). Relative to the control, the treatment had 9% - 14% higher LMC, a relatively small elevation from the practical standpoint, albeit statistically significant ($p<0.05$).

Daily mean LMC in treatment and control over time is shown in Table 2. Trial 2 had lower LMC than Trial 1 and Trial 3. LMC started to decrease from d15 in Trial 1 in both treatment and control sections (early November 2017), when the outdoor T dropped sharply (fig. 5a) which presumably led to increased use of supplemental heating in the house. This assumption was confirmed by the farm staff, and it can be explained in figure 4b, where the corresponding indoor RH decreased sharply.

Table 2. Daily mean litter moisture content (LMC) and NH_3 concentration in treatment (T) and control (C) during test

	d0	d1	d4	d7	d10	d13	d15	d18	d22	d25	d28
					LMC (%)						
T1-T	14.1	14.5	14.9	15.3	15.3	15.6	14.0	13.5	12.5	12.4	12.1
T1-C	14.4	14.1	13.7	13.9	13.6	14.0	13.9	13.6	12.7	12.2	12.3
T2-T	11.6	12.2	13.0	13.7	14.3	14.6	13.1	12.3	12.0	11.0	-
T2-C	11.4	11.5	11.7	12.0	12.3	12.2	12.0	12.4	12.3	10.8	-
T3-T	13.2	14.6	16.0	16.8	17.5	17.7	16.0	15.7	15.3	-	15.4
T3-C	13.5	13.8	14.3	15.3	15.2	14.9	14.8	15.3	15.0	-	15.2
					NH_3 concentration (ppm)						
T1-T	3.0	2.7	3.5	6.7	8.8	11.2	10.1	6.5	5.4	7.2	7.0
T1-C	3.2	2.9	3.8	6.4	9.2	11.7	9.8	7.3	5.9	7.7	7.5
T2-T	6.0	5.4	4.1	3.9	6.8	8.0	6.8	7.1	6.5	8.6	-
T2-C	6.4	5.7	4.7	4.2	7.1	7.8	6.5	7.0	6.7	9.1	-
T3-T	15.5	19.9	21.6	15.7	8.4	13.6	16.2	25.7	10.1	-	11.2
T3-C	16.0	19.4	20.7	15.1	8.8	13.1	16.8	27.9	11.0	-	11.6

Note: T1, T2, and T3 – Trial1, Trial 2, and Trial 3; Litter on d28 in Trial 2 and on d25 in Trial 3 was not sampled; data on d28 of Trail 2 and on d25 of Trail 3 were not collected.

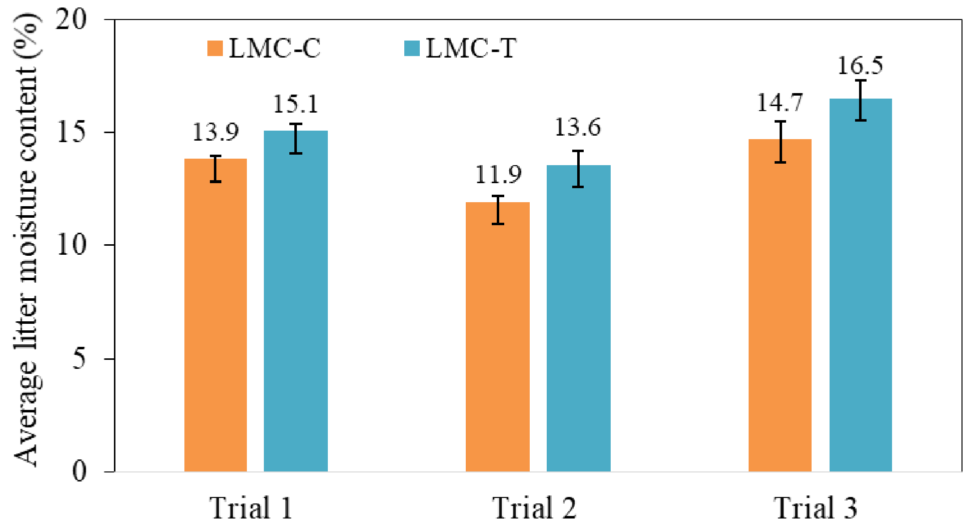


Figure 7. Litter moisture content (mean ± SE of d1, d4, d7, d10, and d13 with once-a-day spray; LMC-T and LMC-C represents litter moisture content in the treatment and control section, respectively. In treatment, spray dosage was 62.5, 125, and 175 ml m^{-2} during Trial 1, 2, and 3, respectively).

Figure 8 shows the NH_3 concentrations of the treatment and control sections during the test. Table 2 lists daily mean NH_3 concentrations. The treatment and control had similar NH_3 levels across each trial. The spray dosage of 125 mL m^{-2} per cm litter depth did not elevate NH_3 level ($p=0.104$). Trial 3 had higher NH_3 level than the other two due to colder weather and lower VR.

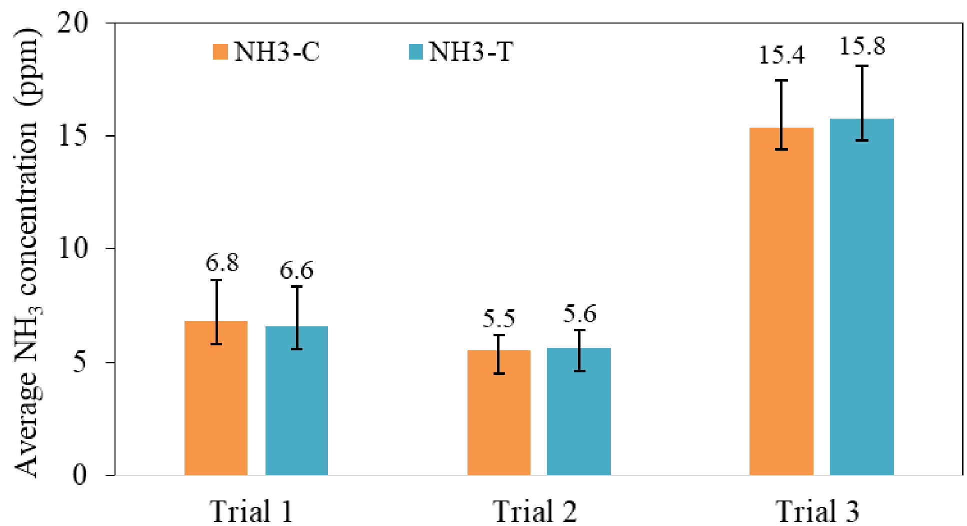


Figure 8. Ammonia concentration in the treatment and control (mean ± SE of d1, d4, d7, d10, and d13 with once-a-day spray;

NH3-T and NH3-C represents NH_3 concentration measured in the treatment and control section, respectively. In treatment, spray dosage was 62.5, 125, and 175 ml m^{-2} during Trial 1, 2, and 3, respectively).

PARTICULATE MATTER (PM) CONCENTRATION AND REDUCTION EFFICIENCY

Figure 9 is an example of diurnal PM levels in the CF henhouse in late October of 2017. PM levels varied throughout the day, especially during feeding, lights on/off, and litter-access periods. The PM profiles agreed with those reported by Zhao et al. (2015). There were vertical stratifications in the PM levels, with higher levels being closer to the litter floor (fig. 10) – the primary source of dust generation.

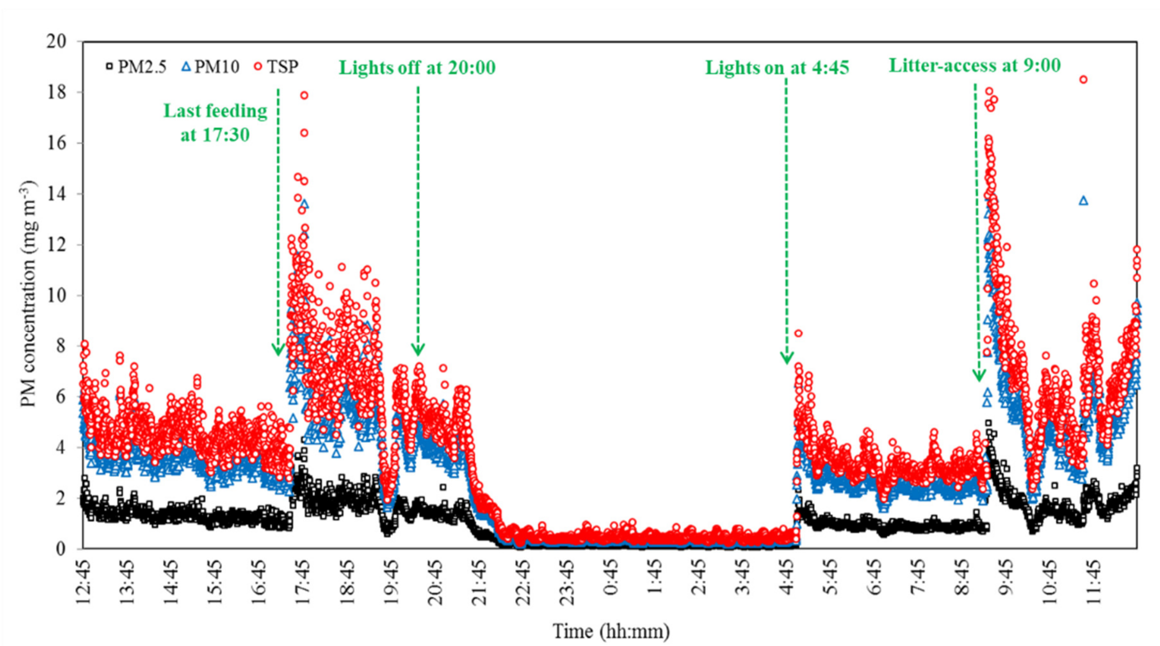


Figure 9. Diurnal particulate matter concentrations 0.25 m above litter level (Oct. 24-25, 2017).

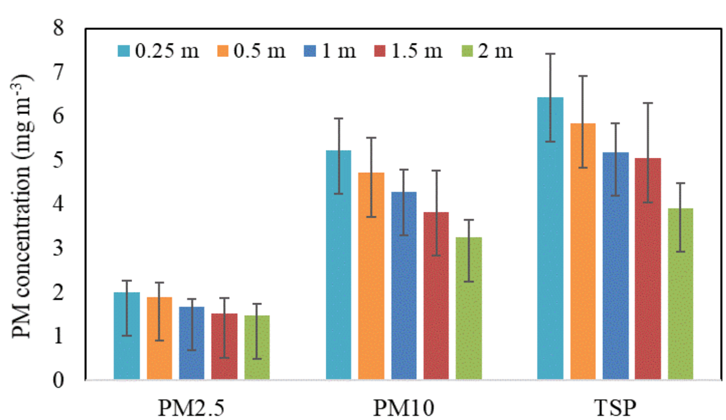


Figure 10. Vertical distributions of PM2.5, PM10 and TSP concentrations in the cage-free henhouse (mean ± SE of PM levels measured in selected locations (R2S2, R2S4, R2S7, and R2S9) on Oct. 24, 2017.

The proportion of PM_{10} in TSP, as monitored by the DustTrak optical sensor, was as high as 70-80% in this study, which was higher than the value of 35-40% reported by other researchers such as Li et al. (2013). The differences could have been partially attributed to the different measurement methods and housing types between the two studies. The latter study used Tapered Element Oscillating Microbalance (TEOM) sensor for PM measurement in high-rise layer henhouses where the primary dust sources and size distribution may differ considerably from those in CF houses. In addition, measurements by DustTrak have been reported to underestimate PM levels in poultry houses as compared to the reference methods of TEOM and gravimetric samplers. The ratio of DustTrak to TEOM or gravimetric measurement of PM10 has been reported to vary from 0.41 to 0.80 (Cambra-Lopez et al., 2015; Winkel et al., 2015) in the Netherlands. Li et al. (2018) reported a ratio of 0.244 in a US layer breeder house. However, the DustTrak optical sensor was used in this study to determine the reduction efficiency on PM level by water spray. As such, the potential system bias in measurement of the actual PM concentrations by the DustTrak would have rather minimal impact on the change in PM concentration caused by water spray, hence validity of the results.

Before spray (d0) in each trial, PM levels in the treatment and control were similar (fig. 11). After implementing spray (d1-d14), the difference became clear, and the treatment had significantly lower PM levels ($p<0.05$). One day after stopping the spray (d15), there was still some difference between the two regimens; but the difference disappeared 4 d after suspending the spray (d18). This finding agreed well with results of our lab-scale test (Chai et al., 2018a). The reduction efficiency during three trials is shown in Figure 12. The PM of different sizes in the treatment was 37-51% lower than in the control for the three trials. Reduction efficiencies for PM_{10} and TSP are higher than that for $PM_{2.5}$. Higher spray dosages reduced PM levels further ($p<0.05$ for different PM sizes most of the time except for $PM_{2.5}$ in trial 3), but not proportionately because the birds would mix the top and bottom of the litter during foraging and dust bathing. Therefore, adjusting spraying dosage according to litter depth is necessary. In addition, reduction efficiency in the field was lower than that observed in the lab test (60-70%) (Chai et al., 2018a) because of lower spray coverage. In the field, water was sprayed only onto the open area of the litter floor, not under the aviary structures. Further PM reduction may be achieved by exploring a different approach or sprinkler/nozzle design beneath the aviary structures without being damaged by the birds.

The PM reduction efficiency observed in this study similar to that (49%) reported by Zheng et al. (2014) with 80 mL m^{-2} tap water spray. However, the PM_{10} reduction efficiency was higher than the result (18%) reported by Ogink et al. (2012) at

150 mL m^{-2} water spray in a CF henhouse in the Netherlands and the result (34%) reported by Zheng et al. (2012) at 216 mL m^{-2} for a layer breeding house in China. A number of reasons could have contributed to the differences, such as measurement method, sprinkler installation (coverage area, and installation height), litter quality (e.g., LMC, litter depth, and bedding materials used), and flock management (e.g., lighting and feeding schedule, laying hen breed/age and activity levels, and indoor environmental factors such as RH). The current study adjusted spray dosage according to the litter depth, which maintained PM reduction performance. Research is needed to test the effect of different spray dosages × litter depths on PM reduction efficiency in commercial cage-free houses.

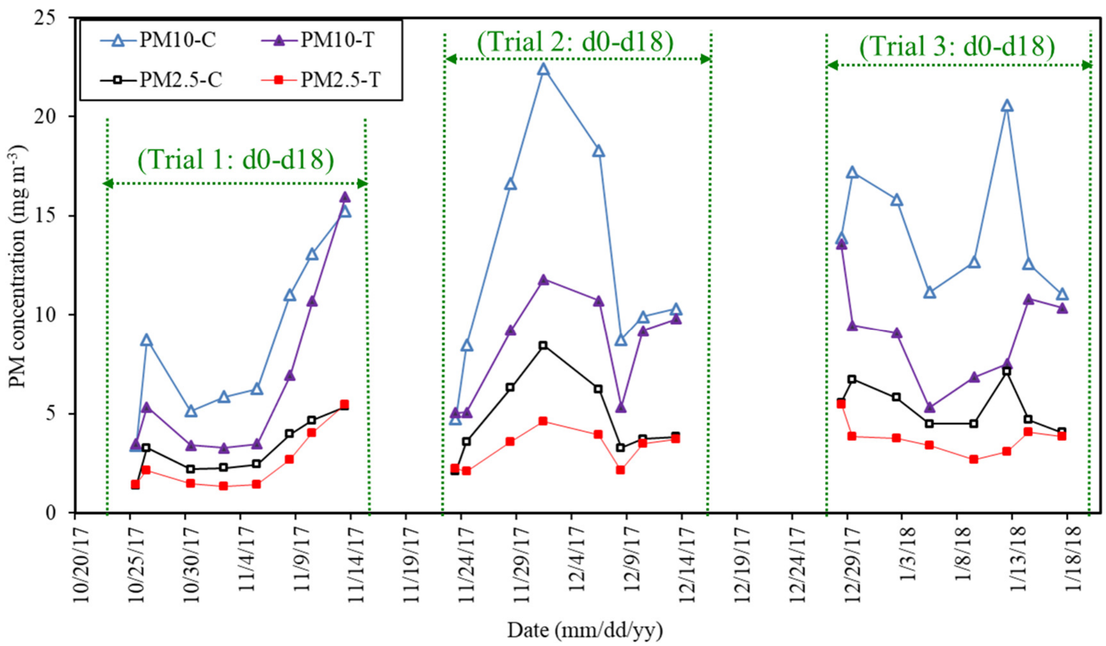


Figure 11. PM levels in the treatment and control (monitored on d0, d1, d4, d7, d10, d13, d15, and d18 in each trial; d0 was October 26, 2017 for Trial 1, November 24, 2017 for Trial 2, and December 29, 2017 for Trial 3).

Uncertainty may exist in PM concentration measurement as the treatment and the control was not monitored at the same moment. At the beginning of this study, two PM sensors were newly calibrated intending to monitor PM in treat and control sections simultaneously. However, two TSI sensors were found with over 1 mg m^{-3} bias at the same measurement location when indoor PM level (e.g., PM10) reached 10 mg m^{-3} or higher, although they agreed well with each other when indoor PM level was lower than 5 mg m^{-3}. Therefore, only one PM sensor was used for the measurement. The whole house measurement was completed in around 1 h, but the measurement in each row was completed within 15 min. The PM reduction efficiency in each row was calculated first, then the results in four rows were averaged as the whole house PM reduction efficiency of the day. The PM measurement in CF house needs to be further improved by using real-time monitoring method in treatment and control sides at the same time in the future. During PM measurement, farm staff were informed and no nobody entered the house. In addition, the house ventilation was not monitored during this test. Instead, the CO_2 concentration was used as an indicator of house ventilation change and the airflow similarity for treatment and control. This study can be improved by monitoring the house ventilation continuously and the airflow rate in treatment and control sides simultaneously.

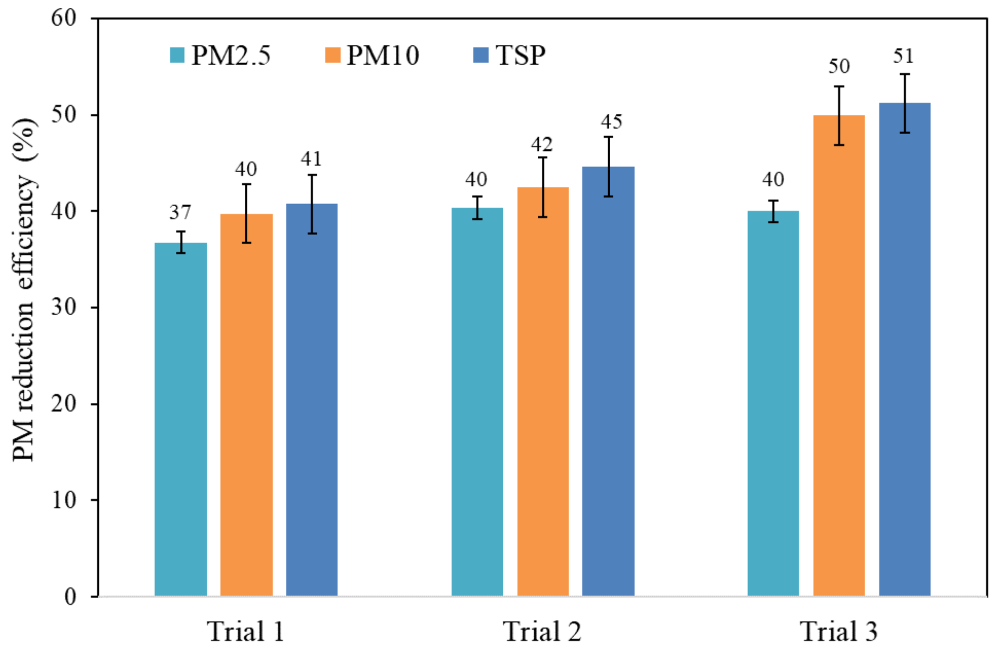


Figure 12. PM reduction efficiency (mean ± SE of d1 to d14 with once-a-day spray).

Water spray is one of the most cost-effective dust mitigation strategies (Chai et al., 2017; Winkel, 2016). This study was conducted in a commercial CF houses with 50,000 laying hens, and the water spray covered area was 600 m^2 litter floor for half of the house. The total water usage for dust reduction would be 150 L per day for covering a full house of 1200 m^2 open litter floor area or approximately 3 mL $bird^{-1}$ d^{-1} per cm of litter depth based on the spray dosage of 125 ml m^{-2} per cm litter depth.

Summary and Conclusions

Spraying water at 125 mL m^{-2} per cm litter depth, once a day shortly before access of litter floor by the hens, reduced indoor PM levels by 37-51% as compared to no-spray in a commercial aviary cage-free henhouse during winter season. PM reduction efficiency increased with spray dosage in a non-linear fashion. Adjusting spray dosage according to litter depth is necessary to maintain appreciable PM reduction efficiency.

Under the current spray scheme of once-a-day spray over 14 d, there was little impact on ammonia level. Litter moisture content in the treatment was 9-14% higher relative to no-spray.

The current spray scheme for a 50,000 hens cage-free house with 1200 m^2 open litter floor area would have a daily water usage of approximately 150 L or 3 mL $bird^{-1}$ d^{-1} based on the spray dosage of 125 ml m^{-2} per cm of litter depth.

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